Functional Assessment of Lightweight Construction Solutions in View of Sustainability

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ABSTRACT: The amount of waste produced every year, the exhaustion of resources and the construction solutions currently used on construction may not be sustainable in the future. All these issues lead to the research of new construction techniques, the recycling of waste into useful materials, the re-use of construction materials, etc. Most of the new and innovative solutions arise from the general feeling that something should be done to change the conventional way of construction in order to give an answer to current society concerns: the reduction of energy consumption, the minimization of pollution problems, the maximisation of the use of renewable and/or recyclable materials, etc. The aim of this study is to evaluate the potentialities of using more lightweight construction solutions with respect to functional comfort criteria (thermal, acoustic and visual comfort) and to assess the relative merits of this type of construction in view of maximising sustainability. Beyond the structural behaviour of a building the demand of a better habitat requires also a good performance in terms of serviceability. In this work the performance of lightweight construction solutions (optimized for reducing environmental impact) and conventional construction solutions were compared under the energy costs point of view (construction and heating). The acoustic performance was also studied, but just in order to achieve similar conditions, thus becoming not relevant to the purpose of this study.

1 INTRODUCTION

1.1 *Historical evolution of housing construction systems in Portugal*

In the past centuries, at least until 50 years ago, in spite of an extremely heavy stone or massive brick envelope wall (it arrives to more then 1000 kg/m^2), some of the construction elements in housing buildings in Portugal were lightweight, mainly timber pavements (approximately 50-100 kg/m^2), timber/clay dividing walls and timber covering structures (approximately 150- 200 kg/m^2). Recently, with the generalisation of steel reinforced concrete and industrialised hollow bricks, the more usual attitude is to generalise the use of the so called “lightweightened” concrete construction system (with approximately 350-400 kg/m^2 for a 0,22m pavement slab and a similar weight for a double pane hollow brick envelope wall, generally with insulation on the air gap) in conventional housing buildings. We can conclude that, in spite of some relative increment on structural performance, the average weight of a housing building is very similar to 50 years ago, but the environmental impact costs per square metre have increased and the possibilities of recycling their components have decreased (Mendonça 2003).

Reducing the specific weight of industrialised construction materials and systems can in fact have a significant role on reducing environmental costs, namely by the use of prefabricated modular systems that require no cranes and other heavyweight equipment to erect and have smaller energy costs associated with transport and even with the construction materials themselves. One main problem is that lightweight buildings are usually characterised by a small thermal inertia that results in an excessive daily thermal temperature swing, and thus they are not usually considered on bioclimatic approaches on temperate climates.

1.2 *Objectives*

The general objectives of this work are shown on Figure 1. There are several strategies that can lead to reduce the environmental impact of buildings. Recycle and re-use of the materials and even the buildings itself are possible, but are not the issue to be discussed on this paper. The strategy proposed here will be based on the reduction and how it can be achieved by optimizing the weight on architectural and construction systems. There will be focused two different aspects: one is a research on optimizing the total primary energy consumption (PEC) of construction materials and their transport, the other is based on reducing the energy operating consumptions for maintaining thermal comfort, even using the maximum possible passive solar gains. In order to compare the relative influence of these aspects, measurements were carried out on two solar passive test cells.

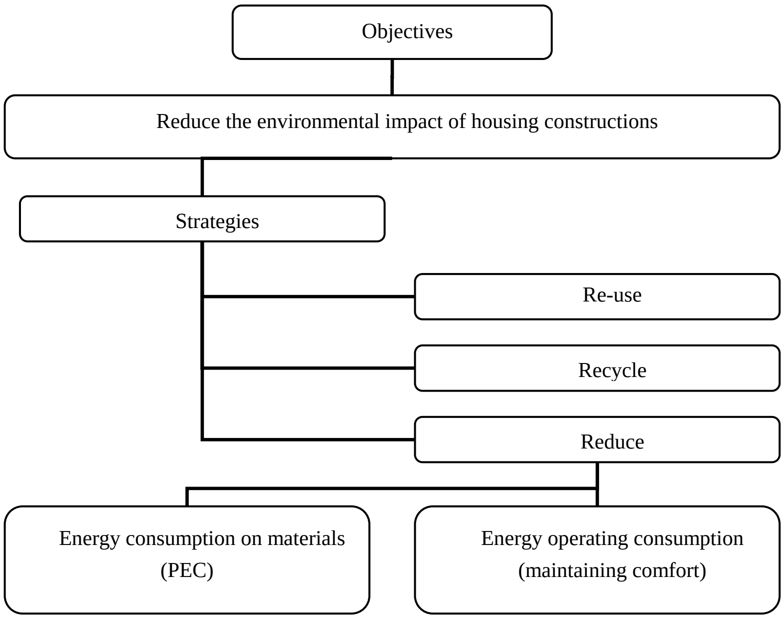


Figure 1. General objectives of this study

2 ENERGY CONSUMPTION ON BUILDINGS

2.1. *Reducing energy consumption on construction*

Reducing the weight of materials used implies smaller environmental damages due to the extraction of prime materials, to their transformation processes and to the work yards, with reduction of the noise, dust, wastes and the consumption of energy during the construction and a proportional reduction on loss factors and specially on transport energy costs. The maximum use of local and less-transformed raw materials, or recycled ones, means reduction. But also the minimum use of those that are not locally available, such as steel for reinforcing concrete, cement, brick and an optimized use of those that, in spite of not being local or low energy, can compensate on savings, over their lifespan, such as glass or insulation. We should have in mind that a road transport by truck implies 2890 kJ/t/km (802,78 kW.h/kg.km), being one of the most pollutant ways for transporting construction materials, as can be seen on Table I, and this is the most used mode of transport in Portugal.

Table I. Primary energy use by different modes of freight transport (Energy Research Group 1999)

Emissions (g /T.Km)	Water	Rail	Road	Air
CO_2	30	41	207	1206
CH_4	0.04	0.06	0.3	2.0
NO_x	0.4	0.2	3.6	5.5
CO	0.12	0.05	2.4	1.4
VOCs	0.1	0.08	1.1	3.0
Energy (kJ/T.km)	423	677	2890	15839

2.2. *Reducing operating energy*

In what respects the structure and the materials used, bioclimatic housing buildings in South European climates are even more heavyweight than conventional ones. Concrete and brick are used in the interior pane of double envelope walls and in pavements, in order to increase thermal storage capacity. But it could be questioned if the overall weight could not be reduced by introducing more accurate systems. When the materials and labour are locally available (as adobe or stone), the environmental cost is reduced, but the increase of the global mass of the building implies other problems, such as the high economical cost of an intensive labour or the difficulty for increasing density by the increment of floors (even to more than two). Thermal mass materials still should be used, but in a rational way, related to local availability and just to fit thermal storage necessities. Some construction elements cannot be always locally available, (such as steel, concrete, ceramics and specially glass), and thus this is an area where optimisation can be even more effective (Mendonça 2003).

In housing, the thermal gains could be higher in a direct gain strategy, with the concrete pavement slab, the interior walls and the interior pane of exterior walls taking the role of thermal storage, but the temperature and glare due to excessive solar radiation penetrating the interior occupied areas are a cause of discomfort. Apart from the degradation of the furniture and other equipment, a direct gain strategy is not a good solution, also due to the necessity of daily operating a night mobile insulation system. An indirect gain solution could be more effective in order to keep interior comfort in a more functional way, and guarantees that project values are closer to reality.

3 TEST CELLS STUDY

3.1. *Characterization of the test cells study*

The proposed strategy of reducing the overall environmental impact of buildings was based on a mixedweight housing principle, with a thermal zoning concept and passive solar indirect gain that was expected to lead to an overall weight reduction on construction but without increasing operating energy. A research was undertaken using two test cells simulating areas of the Architectural designs shown on figure 2. The plan on the left is the proposed mixed weight and mixed use housing unit (working on North area with direct lighting and sleeping on South area with indirect solar gains). The right plan simulates a conventional housing unit (but it has also an optimized solar exposition and mixed direct / indirect solar gains).

Figure 2. Plans of proposed and conventional housing units (Mendonça 2003)

The Test Cells studied have a rectangular shape (approximately 6,5x3,1m), both are South oriented and have an horizontally moving window that is able to perform a sunspace or a Trombe wall as shown in Figure 2 on the right side.

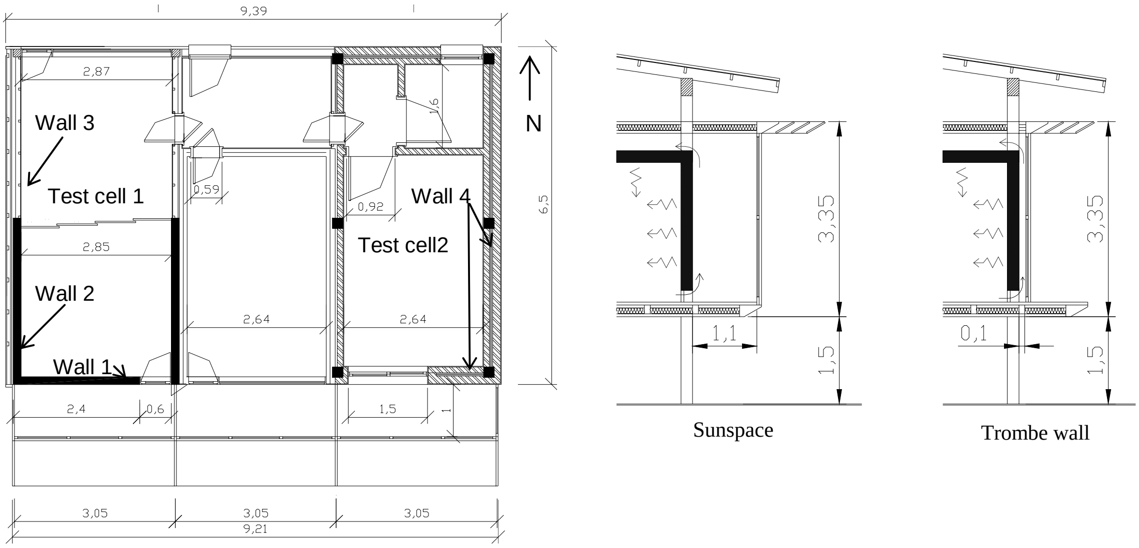


Figure 2. Test cells' plan and schematic vertical section of moving window (through wall 1) to create a Sunspace or a Trombe wall (distances in m).

Test Cell 1 is the non conventional cell, where the thermal performance of the mixedweight construction was studied. This test cell is divided in two parts separated by a wood moving partition: an heavyweight South oriented zone (sleeping area) with concrete structure, pavement and ceiling slabs, adobe walls and a North oriented lightweight zone with timber structure and sandwich pavement, ceiling and walls. In the heavyweight area Wall 1 is an adobe thermal gaining wall without insulation and a black painting exterior finishing and Wall 2 is a double pane wall with a 15 cm adobe pane on the interior and a wood cement exterior board with a ventilated 15cm air gap with 5cm expanded cork insulation. The North oriented zone (working area) has sandwich lightweight pavement and ceiling made with wood cement board and expanded cork insulation and triple pane walls with an exterior ventilated 15 cm air gap and an interior super-insulated air gap with 8cm of expanded cork + 2cm of coconut fibre.

For comparative analysis, a conventional reference cell, named Test Cell 2 on Figure 2, with the same dimensional characteristics, but made with a conventional construction solution, was also studied. This cell corresponds to a conventional solution on contemporary Portuguese construction and has a construction system based on a steel reinforced concrete structure, with pavement and ceiling on pre-stressed concrete “T” beams and hollow brick and exterior double pane (15+11 cm) hollow brick wall with 4 cm of extruded polystyrene (XPS) placed in the air gap and finished with plaster on both sides.

Figures 3, 4 and 5 show the vertical schemes of the façades and a vertical section of each test cell.

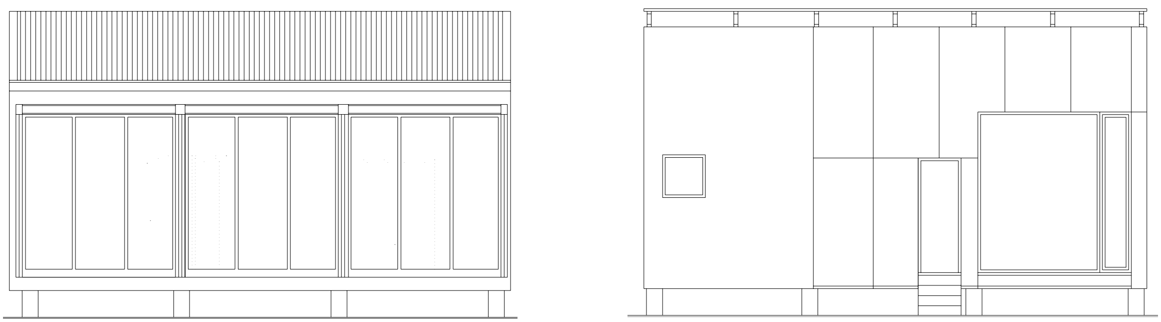


Figure 3. Test cells' vertical scheme of the North and South façades.

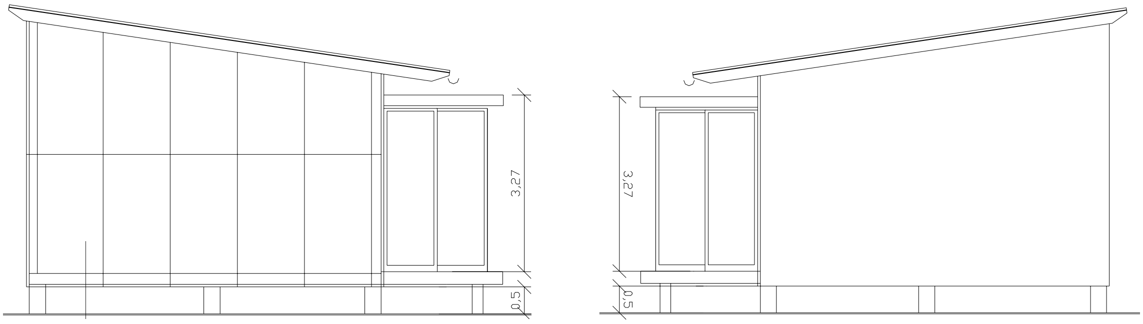


Figure 4. Test cells' vertical scheme of the East and West façades (distances in m).

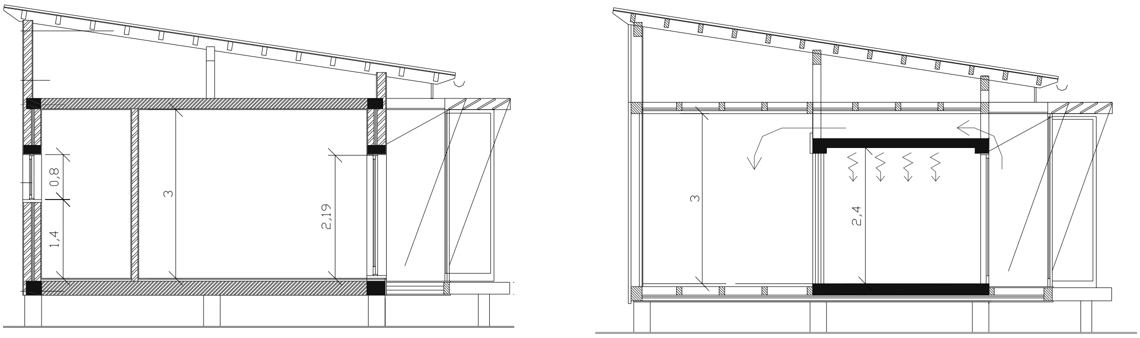


Figure 5. Vertical sections of test cells 1 and 2 – sunspace configuration (distances in m).

3.2. Energy operating consumption

Long term energy savings implies more than a correct design of façades. In countries with an annual and daily thermal amplitude oscillating below and above the temperature of ideal interior comfort, such as Portugal, where this study is being made (between a minimum of –2,5^{o}C and a maximum of 35^{o}C) and a daily thermal amplitude of 10^{o}C (Mendes et al. 1989), thermal inertia is even more important than insulation capacity, as its absence can result in a night rapid descent of temperature and a resulting excessive daily thermal swing in the interior. Since the South facing walls can take the main role of thermal gains, the bet can be to optimise their performance, and so to use it mainly for indirect gain. The use of combined solutions of ventilation / heat storage, namely by the use of Trombe walls is an effective method of natural heating during the cold season, when there is enough solar radiation. One problem is that the construction of these interior walls between the window and the occupied zones decrease interior illumination, for they are opaque. The need of a great window surface oriented to South and with its major area closed by thermal gaining opaque walls forces the building to open more to other solar orientations. In the proposed solution the working area for studying, receives natural illumination through a translucent window (in alveolar polycarbonate and timber frame) oriented to North. This North great light capture causes more fluctuation on the interior temperature, but it also permits to have a more uniform lighting for this area, that was expected to have a daytime occupation (working areas). The heavyweight area have a smaller fluctuation and when the partition door is closed, during night hours, the temperature swing in this area is lower then the reference test cell. Summer campaign measurements also revealed that cooling needs were not relevant, so they were not considered (the zone of this study was Guimarães and it is in a Northern temperate area of Portugal – not very far from sea so it still gets some maritime influence). The heating overall energetic needs were measured and calculated using the method proposed by CSTB (CSTB 1988) and these values were compared with the other energy aspects - primary energy of construction materials (PEC) and materials transport.

4. ENERGY COST EVALUATION

Table II presents the measures of the Embodied Energy of materials used in the proposed test cell (1) and in the reference test cell (2). As we can conclude from the analysis of this table, in Test Cell 1 and 2, the aluminium of the exterior window frames, in spite of being lightweight, have a very high PEC. Aluminium was the solution adopted here just for the specific purpose of being a mobile window (it makes a telescopic movement in order to study the influence of the sunspace area in the thermal gains as it was referred previously), and other solutions were not exequible for this purpose. In a real situation, a wood frame on the frontal window of the sunspace or the Trombe wall would have a much smaller embodied energy. Those are the values referred in parenthesis and it can be seen that the total PEC decreases 43% on the proposed solution. On conventional construction, hollow brick and concrete take the greatest portion of the embodied energy.

Table II. Embodied energy and weight of materials used in proposed and conventional test cells

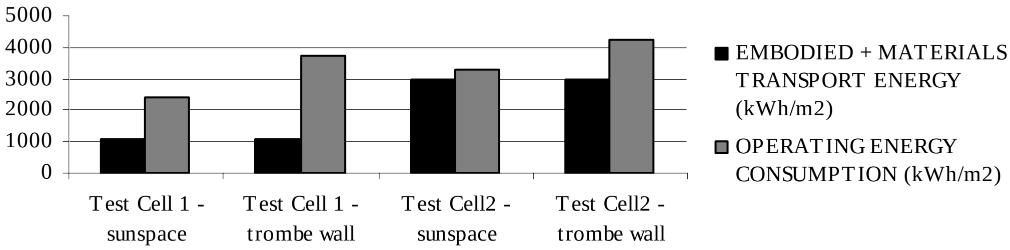
Test Cell 1 (Proposed)	MATERIALS USED	WEIGHT (kg)	kWh/kg	PEC(kWh)
	Aluminium (commercial 30% recycled)	200,00	44,48	8896,00
	Concrete	18344,80	0,33	6053,78
	Particle board (cement / wood)	2161,35	1,08	2334,26
	Steel (commercial 20% recycled)	681,32	2,78	1894,07
	Insulation (expanded cork particle board)	884,40	1,11	981,68
	Stainless steel	75,00	9,73	729,75
	Vulcanized rubber (exterior board fixing sealant)	34,00	19,44	660,96
	Glass	106,80	5,11	545,75
	Asphalt / carton shingle	112,50	4,05	455,63
	Carton / plaster gypsum board	397,80	1,05	417,69
	Alveolar polycarbonate	16,39	24,19	396,47
	Timber (local treated pine)	1971,27	0,18	354,83
	Gypsum (projected plaster)	306,00	1,05	321,30
	Insulation (Coconut fibre)	57,80	3,90	225,42
	Synthetic varnish	9,50	21,55	204,73
	Timber floating pavement	107,10	1,39	148,87
	Adobe	4995,00	0,03	134,87
	Particle board (wood)	83,49	1,08	90,17
	Lime painting (slaked)	144,00	0,28	40,03
	Polyethylene shingle (expanded)	1,53	24,19	37,01
	Plastic painting (water based)	3,60	5,56	20,02
Total (with aluminium frame on solarspace)		**30693,65**		**24943,28**
	(timber frame)	80,00	0,18	14,40
Total (with timber frame on solarspace)		**30573,65**		**16061,68**
	Pavement area $17m^2$			
Total / m^2 (with timber frame on solarspace)		**1798,45**		**944,81**

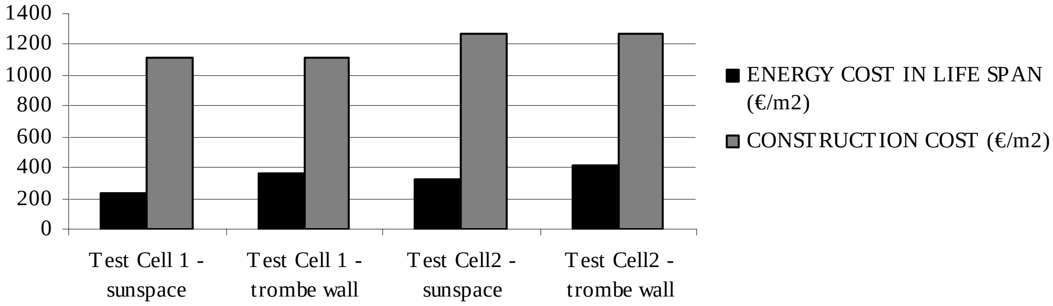
Test Cell 2 (Conventional)	MATERIALS USED	WEIGHT(kg)	(kWh/kg)	PEC(kWh)
	Clay (hollow brick)	9778,13	1,26	12320,44
	Aluminium (commercial 30% recycled)	250,00	44,48	11120,00
	Concrete / Cement mortar	32411,60	0,33	10695,83
	Steel (commercial 20% recycled)	955,60	2,78	2656,57
	Polystyrene extruded (XPS)	54,00	27,86	1504,44
	Stainless steel	75,00	9,73	729,75
	Glass	127,20	5,11	649,99
	Asphalt / carton shingle	112,50	4,05	455,63
	Gypsum (projected plaster)	270,00	1,05	283,50
	Alveolar polycarbonate	8,91	24,19	215,53
	Particle board (cement / wood)	153,90	1,08	166,21
	Timber (local treated pine)	851,13	0,18	153,20
	Timber floating pavement	94,50	1,39	131,36
	Plastic painting (water based)	11,70	5,56	65,05
	Particle board (wood)	40,32	1,08	43,55
	Synthetic varnish	1,70	21,55	36,64
	Polyethylene shingle (expanded)	1,35	24,19	32,66
Total		**45197,54**		**41260,33**
	Pavement area $15m^2$			
Total / m^2		**3013,17**		**2750,69**

For the comparative cost analysis presented on Table III, where it can be seen that the proposed solution is a little more economical, the life span considered was 50 years with a 2,5% inflation rate. The operating costs were considered just for the heating season, in a 18ºC base temperature and heating with electric wall radiators. Note that in certain regions of Portugal, stone would be preferable to Adobe masonry in interior heavyweight walls on proposed solution, but the average final value would be very similar as stone has the same PEC.

Table III. Embodied energy, operating energy economical and energetic costs in a 50 years life span

Test Cell		OPERATING ENERGY COST IN LIFE SPAN (€/m^2)	CONSTRUCTION COST (€/m^2)	EMBODIED ENERGY (kWh/m^2)	MATERIALS TRANSPORT ENERGY (kWh/m^2)	OPERATING ENERGY CONSUMPTION (kWh/m^2)
1	sunspace	235	1111	1470	121,4	2374,5
	trombe wall	369				3728,5
2	sunspace	323	1267	2756,6	241,9	3261,5
	trombe wall	417				4218,5





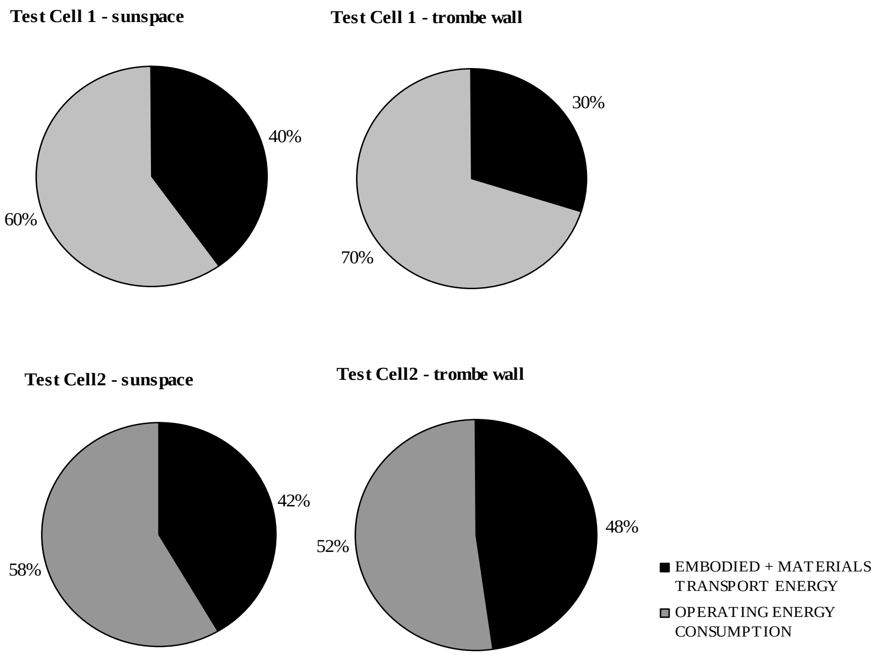


Figure 6, 7 and 8. Comparisons between operating energy and embodied + transport energy of test cells.

The reduction in weight was in a great part from industrialised non-locally available components, so the percentage of reduction associated with transport, mainly truck by road was significant. To the transport study was considered that all materials made an average of 100 km. The average distance in the transport of adobe (compacted earth) was considered to be 0 km.

A Nordic author says that “The amount of energy that actually goes into the production of building materials is between 6 and 20 % of the total energy consumption during 50 years of use, depending on the building method, climate, etc”(Berge 1999). The percentage that most suits the Portuguese reality is maybe closer to 20 %, because of the particular amenity of the climate, but we can even state that the amount of energy that goes into the production of building materials can easily reach values between 30 to 48% of the total energy consumption during 50 years of use.

5. CONCLUSION

This paper show the potentialities associated with the use of lightweight materials combined with locally available thermal mass materials, in order to achieve a good environmental profile. In the end of the life span of most contemporary housing buildings, the dismantling, treatment and transport of waste materials also represents energy savings. The proposed solution is also easy to dismantle and almost all of its materials are reusable or recyclable, especially if compared with nowadays most common construction system used in Portugal – steel reinforced concrete structure with clay hollow brick walls and pavements. The example presented in this paper shows how the environmental impact measured on the Primary Energy Consumption of materials in the proposed innovative mixedweight test cell can reach almost a 50% of improvement when compared with a conventional one and still having a similar economical cost (even a little lower). In spite of the increasing evolution that lightweight materials and systems achieved in the recent past, namely to their durability and stability there is still a long way to go through, before these solutions can be widely accepted. Mixing them with heavyweight solutions, and proving the fact that this strategy is environmentally suitable to be used in bioclimatic constructions, even to temperate climates as the South European ones, can be a step forward. It could also be concluded that the solar passive optimized solution is more sustainable in a Sunspace configuration then in a Trombe wall configuration.

6. ACKNOWLEDGEMENT

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